

Status Report

**IDENTIFICATION OF CROSS-FORMATIONAL FLOW IN MULTIRESERVOIR SYSTEMS
USING ISOTOPIC TECHNIQUES (PHASE I)**

Project SGP 43, Milestone 1, FY91

By

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ABSTRACT

The project was initiated in mid-August of 1990. The study has been designed to add quantitative and sometimes unique solutions to the problem of undesirable hydraulic intercommunication conventionally detected by analysis of anomalous well production and costly pressure buildup tests, interference tests, and tracer tests. The emphasis at this state of the project has been on searching for (1) reported evidence of dynamic conditions in multireservoir systems, (2) field applications of geochemical (including isotopic) methods to identify cross-formational flow and (3) spectrum of the best suitable isotopes and analytical costs.

In most reviewed cases, the scale of natural and man-induced cross-formational flow of fluids such as hydrocarbons, formation water, non-hydrocarbon gases, and chemicals varies between hundreds and thousands of feet.

According to the working hypothesis adopted in this project, the formation fluids which are compartmentalized in isolated and often overpressured hydraulic systems should possess generally similar chemical and isotopic characteristics within a system. Differences in fluid origin and specific isotope fractionation processes should lead to a distinct isotopic composition in such systems.

A break in continuity of a confining layers, (which may be of depositional, erosional, tectonic, or physical nature), will promote interreservoir migration of fluids. Such fluid flow should result in chemical and isotopic anomalies in the area of an open flow path.

In case of exceptionally active subsurface drainage of fluids along, (for example, an open fault zone, hydraulic fracturing zone, breccia pipe, or unconformity), a deep water discharge (DWD) will cause effective mixing and geochemical homogenization of formation fluids in such a system. Several cases of DWD's in oil fields have been reviewed.

Geochemical methods including isotopic techniques add a quantitative aspect to some of the reviewed cases where hydrodynamic conditions are well documented. These cases are being further investigated.

INTRODUCTION

Effective tracing of fluid flow barriers and conduits between productive horizons or reservoirs is vital at any stage of field development. Prediction and control of fluid migration paths, however, are particularly critical at the stage of enhanced oil recovery (EOR). Fluid heterogeneities and flow characteristics are usually less adequately addressed than reservoir rock systems. Most case studies emphasize reservoir characterization of properties of the reservoir container rather than the reservoir content and its mobility. In such a system where fluid heterogeneities are poorly recognized, the reservoir characterization is incomplete, and the fluid flow cannot be effectively predicted. Observations on hydrocarbon migration phenomena in sedimentary basins debated at the Second French Petroleum Institute (IFP) Research Conference led to the conclusion that the number of well documented case histories, based on proper geological and geochemical information, presently available is very low, and more examples are definitely needed.¹ Several active and dominantly ascending systems of fluid migration from a source rock to pools in the shallow hydrogeological system (or to the surface) have been documented worldwide. Specific mechanisms, pathways, and velocities of fluid flow between individual productive horizons in a system, however, are discussed in only a few cases.

OBJECTIVE

The objective of this project is to substantiate fluid migration patterns into, within, and out of a reservoir by adapting natural isotopic geochemical techniques to the requirements of quantitative hydrodynamic reservoir modeling. If the study determines that identification of cross-formational flow using recent advances in isotopic technology substantially upgrades the quality of reservoir characterization, recommendations will be made to utilize identification of isotopic makeup of formation fluids for enhancement of oil production from multireservoir systems. Practical demonstration of the method in a selected reservoir will also be recommended as Phase II of the project.

Summary of Technical Progress

This project was initiated in mid-August of 1990. A computer-assisted literature search and review of dynamic aspects of multireservoir systems and application of geochemical methods for identification of cross-flow between reservoirs is about 75% completed. In most reviewed cases, the scale of natural and man-induced cross-formational flow of fluids such as hydrocarbons, formation water, non-hydrocarbon gases, and chemicals varies between hundreds and thousands of feet.

Structural and stratigraphic predisposition promoting interreservoir fluid migration in several major oil and gas reservoirs worldwide has been investigated. Stratigraphic and structural framework has been

reviewed from this point of view for such typical super-giant fields as Urengoy (USSR), Ghawar (Saudi Arabia), Samotlor (USSR), Handil (Indonesia), Prudhoe Bay (U.S.), Lake Maracaibo (Venezuela), Brent (North Sea), Gaschasan (Iran) and some domestic multireservoir fields; (West Ranch and Northmarkham-North Bay City, TX or Big Muddy and Patrick Draw, WY). The correlation between hydrocarbon accumulation controlled by structural features and stacked reservoirs is striking for a number of domestic and foreign oil and gas fields.

Indonesian Handil, East Kalimantan multireservoir oil field produces from a transversely faulted anticline with some 150 independent reservoirs between depths of 450 m and 2,900 m.² Figure 1 illustrates a general arrangement of productive horizons in Handil field. Figure 2 provides a closeup of a complex organization of productive deltaic sandbodies between R9 and R10 coal markers within a main-interval in figure 1 and erosional channels cutting through some of them. The incisions provide excellent hydraulic communication paths for formation fluids at a vertical scale of tens of meters. The major fault cutting through the entire field (3,000 m) is considered a seal at the present. However, the oils found in the various reservoirs of Handil field have about the same composition and must have been generated from the same type of organic matter.² Its maturation is too low in the formation surrounding the reservoirs to allow these formations to be the source rock of the hydrocarbons. Indeed, the source rock is located deeper,³ and the upward migration of Handil oil is probably still taking place.² It can be concluded at this point that Handil oil field is generally under dynamic conditions and that its multireservoir characteristics are due to the leakage of hydrocarbons upward from one reservoir to another. However, the time, rate, and conduits of that leakage cannot be estimated without hydrochemical, isotopic, and mass balance analyses.

Oxygen and hydrogen isotopic composition of oil field brines collected at different locations of a number of U.S. sedimentary basins varies in a broad range between the basins and within individual basin⁴⁻⁵ (table 1). These data strongly indicate that reported isotopic compositions represent either different dynamic regimes or that fractionation processes resulting for example from isotopic exchange between oil-associated brine and reservoir rock promote a unique composition in different reservoirs of the same basin. One can assume, however, that isotopic differentiation within individual basins mostly results from different origin and mixing of reservoir fluids rather than the rock-brine isotopic interaction because rocks normally (except hydrous minerals and hydroxides) do not contain hydrogen for exchange.

According to the working hypothesis adopted in this project, the formation fluids which are compartmentalized in isolated and often overpressured hydraulic systems should possess generally similar chemical and isotopic characteristics within a system. The differences in fluid origin and specific isotope fractionation processes should lead to a distinct isotopic composition in such systems. Calcite is probably the dominant solid phase in oxygen isotope exchange because it is widely distributed and rather

rapidly dissolved.⁴ A subtle difference in isotopic composition between two samples taken from different depths but closely similar geographic position can be caused by fractionation processes such as ultrafiltration through a semipermeable shale membranes. The sign of the difference in a pair of samples indicates the direction of cross-formational flow in that local area. Based on that principle, a downward movement of formation water was postulated on the Gulf Coast, in the Michigan Basin, and on the north flank of the Illinois Basin, but upward in the deeper part of the Illinois Basin.⁶ Upward and out of the basin movement of fluids was indicated in the Alberta Basin by isotopic composition of lateral pairs of samples. Recharge from the west into the Alberta Basin appeared to be blocked by a fault zone. In many cases, however, no measurable lateral effect was observed.⁶ Stronger vertical than lateral isotopic fractionation effect in tectonically undisturbed areas may have resulted from dominantly stratiform arrangement of most of clastic reservoirs. Accumulating evidence indicates that deep saline groundwaters have migrated for long distances across the North American midcontinent with suggested flow rates of about 10 m/yr redistributing hydrocarbons, forming metallic ores, and diagenetically altering sediments.⁷ Isotopic fractionation of formation waters during subsurface migration due to geochemical processes such as precipitation or recrystallization has been extensively studied. Tracing the migration of hydrocarbons and methane by their isotopic composition is based on the assumption that the composition is related to hydrocarbon origin and that no appreciable isotope fractionation has occurred during migration.⁸⁻¹⁰

The modern isotopic pore fluid composition of a number of the North Sea Brent reservoirs in the Bergen High area is incompatible with diagenetic models based on flushing of the Brent aquifer by hot saline water expelled during compaction.¹¹ Produced formation waters largely composed of entrapped meteoric water; are less saline than sea water (about 10 g/L Cl⁻), and have negative oxygen and hydrogen isotope composition: $\delta^{18}O = -1.5$ to -2.3 ; $\delta D = -32$ to -33 .¹² Significant hydrocarbon and compaction fluid may have initially bypassed Brent traps along faults with ineffective seals that later evolved into effective seals with continued Tertiary burial.¹²

A break in continuity of confining layer, which may be of depositional, erosional, tectonic, or physical nature, will promote interreservoir migration of fluids. Such flow should manifest in chemical and isotopic anomalies in the area of an open flow path. The absolute values may not give usable results; however, relative differences expressed as percentages of variations and calculated as suggested by Vuataz et al.¹³ may reveal small positive or negative variations indicating crossformational fluid movement.

Interreservoir communication releases fluid pressure built up by petrostatic pressure or expansion of fluids and the "leaky" reservoirs may gradually become part of an open hydrodynamic system under predominantly hydrostatic pressures. Hydrostatic pressure favors high trapping efficiency while highly overpressured systems may become susceptible to hydraulic fracturing at the top causing severe leakage

of formation fluids. Tilted fault blocks bounded by major normal faults of more than 2,000 m throw have been documented in the Viking Graben reservoir system, North Sea. Where the fault system is considered poorly permeable or impervious, the severely overpressured Jurassic reservoir leaks.¹⁴ Gas escape from the reservoir is much more rapid than water at the same pressure gradient resulting in a very rapid depletion of the gas accumulation and a resultant drop in reservoir pressure. Pressure distribution across the Smorbukk gas condensate and oil fields illustrated in figure 3 explains a reason for actual position of productive and non-productive wells in the area. The cap rock damage by the sudden leakage phenomena, which was documented by numerous examples worldwide,¹⁵ leaves open conduits for fluids migration. Isotopic analyses of the formation fluids within, beneath and above an alleged cap rock should leave little doubts about its integrity.

In case of exceptionally active subsurface drainage of fluids along, (for example, an open fault zone, hydraulic fracturing, breccia pipe, or unconformity) a deep water discharge (DWD) may cause further pressure drop below the hydrostatic level ("underpressured" reservoir).

Roberts¹⁶ provides well documented examples of DWD's from Athabasca, Orinoco, Middle East, and Gulf Coast oil reservoirs. DWD concept of hydrocarbon accumulation has derived from often observed oil and gas seepages carried by the ascending brine toward surface. Active oil seepage at Mene Grande ("Great Seepage") east of Lake Maracaibo, Venezuela provides a spectacular example of DWD process.¹⁷ The Mene Grande overlies Boliver Coastal field, the largest oil accumulation in the new world which occurs under complex structural and stratigraphic conditions.¹⁸

One of the more active Iranian anticlinal seepages of water, hydrocarbons, and deadly hydrogen sulfide lies over the large, shallow, oil productive Masjed E. Suleyman anticline.¹⁶ Miocene Asmari dolomite of the Gachsaran, Iranian giant oil field crops out 15 km east of the productive anticline and about 500 m higher. The pressures in the anticline, however, are not artesian. "Apparently, the artesian head is relieved by DWD via cross-formational flow along the lateral flow path and especially at the crest of the anticline where the cover is thin and weak".¹⁶

Six giant near-surface oil-impregnated rock deposits in Utah are estimated to contain as much as 29 billion barrels of petroleum.¹⁹ Asphalt seeps actively discharging fresh tar from numerous exposures of the Permian White Rim Sandstone (SE Utah) were described by Baars and Seager in 1970.²⁰ The influence of local geologic structures on fluid migration paths and distribution of oil-impregnated sandstone units in these examples is not well documented. Asphalt is apparently seeping from fractures and bedding planes. Continuous flow obviously indicates dynamic communication with either an oil reservoir and/or a source rock.

The spectacular examples of interformational leakage, which finds obvious manifestation at the surface, would be an excellent field laboratory for testing applicability of isotopic techniques to identification of flow paths and actual source of seeping fluids. Isotopic data, however, are not available from those locations.

An interesting application of isotopic data to identification of leakage gas from underground storage reservoirs was provided by Coleman et al. 1977.²¹ Their data suggest that in areas where bacteriogenic methane occurs in the near-surface aquifers, isotopic analysis of methane can be used to distinguish this gas from gas that has leaked from underground reservoirs and/or from distributory pipelines. Bacteriogenic methane has $\delta^{13}\text{C}$ value in the range of -64 to -90 o/oo, whereas the pipeline and reservoir gases have had values in range of -40 to -46 o/oo.

Alekseyev²² in his analysis of reservoirs across the USSR defined three ranges of $\delta^{13}\text{C}$, associated with the means by which gases formed: biogenic zone, -55 to -95; transition zone; -55 to -65; and thermogenic zone, -36 to -58. Isotopic composition of gases in the transition range strongly indicates mixing of gases from different genetic sources. The 10 largest gas fields in the world produce from Neocomian and Cenomanian complexes of the West Siberian basin east of the Ural Mountains. Isotopic and other geochemical indicators suggest that hydrocarbons in Neocomian reservoirs were generated by thermal maturation of organic matter, while methane in the Cenomanian section appears to be a combination of thermogenic and biogenic gas.²³ The Uregoy field (the largest gas field in the world with reserves estimated at 286 tcf) contains twelve geochemically isolated gas and condensate reservoirs in the Neocomian section. The overlying Cenomanian section, (containing 218 tcf of reserves), is hydrodynamically connected across the length of the field, in part by channel sands. Yamburg field, (the second largest field in the world with 170 tcf in gas reserves), is a single, massive, hydrodynamically connected reservoir.²³ A search for original isotopic data from Russian literature which contributed to identification of the isolated and interconnected zones in the supergiant oil/gas/condensate reservoirs is ongoing.

Domestic oil and gas fields such as West Ranch field and Texas Panhandle fields, Big Muddy, Elk Basin, and Patrick Draw, and Teapot Dome NPR No. 3, WY have a potential for, or strong indications of vertical migration of reservoir fluids. These may be targeted next quarter for closer analysis as potential candidates for isotopic sampling to demonstrate the method. Wirojanagud et al.²⁴ implied a hydraulic connection of the Texas Panhandle oil and gas fields with regional hydrodynamics. An isotopic study could possibly demonstrate these postulated interrelationships.

The application of stable isotopes to upgrade reservoir characterization, and reservoir hydrodynamics is gaining oil industry interest in the U.S. Powley²⁵ conducted numerous special studies for Amoco including research on giant oil field characteristics. He was documented a number of deep-seated and oil-bearing fluid compartments. A special study using isotopes to identification of potential crossflow between fluid compartments has been initiated by the University of Arizona under direction of Dr. R. Bassett, NWWA Darcy Lecturer 1988-89 (Powley - personal communication).

The most promising stable and radio-isotope candidates, naturally occurring in reservoir fluids have been preliminary screened, based on previous study.²⁶ The current review of literature, targets developing geochemical methodology for identification of fluid communication between reservoirs. The deuterium and oxygen-18 data appear to be the most applicable and the best quantitative indicators of reservoir intercommunication. Carbon-13, sulfur-34, strontium-87 and probably boron-11 may provide valuable information about the system. Use of chlorine-36, carbon-14, tritium, and iodine-129 may be considered for solving specific problems such as tracing downward leakage from shallower horizons, mixing of injected fluids with reservoir fluids, and sample contamination with drilling fluids or condensate water.

Recommendations for analytical reliability of different laboratories specializing in stable isotope ratio analyses (SIRA) and natural radioactive isotopes have been sought. Laboratories specializing in isotope analyses were preselected based on recommendations of their clients. Three of the laboratories (Krueger Enterprises, Inc. - Geochron. Laboratories, ChemPet Research Corporation, and Global Geochemistry Corporation) were contacted for comparison of offered services, detection limits, analytical accuracy, sampling requirements, and price schedules. This information is crucial for realistic planning of the next step of the SGP43 project.

A reconnaissance of Patrick Draw field in Sweetwater County, Wyoming provided an opportunity to estimate field conditions for sampling of reservoir fluids at wellheads if such study would be considered feasible for the Almond formation in Patrick Draw field.

REFERENCES

1. Tissot, B. Migration of Hydrocarbons in Sedimentary Basins: A Geological Geochemical and Historical Perspective. In: B. Doligez (Ed.) Migration of Hydrocarbons in sedimentary Basins. 2nd IFP Exploration Research Conference, Carcans, France, 1987, pp. 1-19.
2. Verdier, A. C., T. Oki, and A. Suardy. Geology of the Mandil Field (East Kalimantan-Indonesia). In: M. T. Halbouty (Ed.). Giant Oil and Gas Fields of the Decade 1968-1978. AAPG Memoir 30, 1980, pp. 399-421.

3. Durand, B., and J. L. Oudin. Exemple de Migration des Hydrocarbures Dans Une Serie Deltaique: Le Delta de la Mahakam, Kalimantan, Indonesie. Proceedings of the 10th World Petroleum Congress, 1979, v. 2, pp. 3-11 (in French).
4. Clayton, R. N., I. Friedman, D. L. Graf, T. M. Mayeda, W. F. Ments, and N. F. Shimp. The Origin of Saline Formation Waters, 1. Isotopic Composition. Journal of Geophysical Research, 1966, v. 71, No. 16, pp. 3869-3881.
5. Montgomery, C. W., and E. C. Perry, Jr. Isotopic Methods in Hydrologic Studies--An Introduction. In: Isotopic Studies of Hydrologic Processes, Perry E. C. Jr. (Ed.) Selected papers from a Symposium held Sept. 1980, at Northern Illinois University, Northern Illinois University Press DeKalb, Ill., pp. 1-7.
6. Graf, D. L., I. Friedman, and W. F. Meents. The Origin of Saline Formation Waters, II: Isotopic Fractionation by Shale Micropore Systems. Illinois State Geological Survey, Urbana, 1965, Circular 393, pp. 1-31.
7. Bethke, C. M., and T. F. Corbet. Quantitative Analysis of the Tectonic Origin of Deep Brine Migrations Across the North American Craton. In: B. Doligez (ed.). Migration of Hydrocarbons in Sedimentary Basins. 1987 2nd IFP Exploration Research Conference, Carcans, France, pp. 553-554.
8. Johnson, R. C., and D. D. Rice. Occurrence and Geochemistry of Natural Gases, Piceance Basin, Northwest Colorado. 1990 AAPG Bull. v. 74, No. 6 pp. 805-829.
9. Shoell, M. Isotopic Techniques for Tracing Migration of Gases in Sedimentary Basins: Journal of Geological Society, 1983, v. 140, pp. 415-422.
10. Shoell, M. The Hydrogen and Carbon Isotopic Composition of Methane from Natural Gases of Various Origins. Geochemica et Cosmochemica Acta, 1990, v. 44, pp. 649-61.
11. Jourdan, A., M. Thomas, O. Brevart, P. Robson, F. Sommer, and M. Sullivan. Diagenesis as the Control of the Brent Sandstone Reservoir Properties in the Greater Alwyn Area (East Shetland Basin), in J. Brooks and K. Glennie, Eds. Petroleum Geology of Northwest Europe: London, Graham and Trotman, 1987, pp. 951-961.
12. Glasmann, J. R., R. A. Clark, S. Larter, N. A. Briedis, and P. D. Lundegard. Diagenesis and Hydrocarbon Accumulation, Brent Sandstone (Jurassic), Bergen High Area, North Sea. AAPG Bull. 1989, v. 73, no. 11, pp. 1341-1360.
13. Vuataz, F. D., M. Brach, A. Criand, and Ch. Fouillac. Geochemical Monitoring of Drilling Fluids: A Powerful Tool to Forecast and Detect Formation Waters. SPE Formation Evaluation, June 1990, pp. 177-184.
14. Ungerer, P., J. Burrus, B. Doligez, P. Y. Chenet, and F. Bessis. Basin Evaluation by Integrated Two-Dimensional Modeling of Heat Transfer, Fluid Flow, Hydrocarbon Generation and Migration. AAPG Bull. 1990, v. 74, no. 3, pp. 3090335.
15. Hedberg, H. D. Methane Generation and Petroleum Migration: AAPG Studies in Geology, 1980, v 10, pp. 179-207.
16. Roberts III, W. H. Deep Water Discharge: Key to Hydrocarbon and Mineral Deposits. In: Proceedings of the Third Canadian/American Conference on Hydrogeology; Hydrogeology of Sedimentary Basins: Application to Exploration and Exploitation, B. Hitchon, S. Bachu, and C. M. Sauveplane (Eds.), Banff, Alberta, Canada. June 1986. Published by: National Water Well Association, pp. 42-68.

17. AAPG Bulletin, 1990; Cover photo: Active Oil Seepage at Mene Grande ("Great Seepage"), vol. 73, no. 11.
18. Kamen-Kaye, M. Review of Typical Oil and Gas Fields. Anticlinal-Stratigraphic Fields-1. Oil and Gas Journal, July 1989, pp. 65-69.
19. Campbell, J. A., and H. R. Ritzman. Geology and Petroleum Resources of the Major Oil-Impregnated Sandstone Deposits of Utah. 1979, Utah Geological and Mineral Survey, Special Studies 50.pp. 1-24.
20. Baars, D. L., and W. R. Seager. Stratigraphic Control of Petroleum in White Rim Sandstone (Permian) in and near Canyonlands National Park, Utah. 1970 AAPG Bull. v. 54, No. 5, p. 709-718.
21. Coleman, D. D., W. F. Meents, Chao-Li Liu, and R. A. Keogh. Isotopic Identification of Leakage Gas From Underground Storage Reservoirs -- A Progress Report. Illinois Petroleum III, Illinois State Geological Survey, Urbana, Ill. 1977, p. 1-10.
22. Alekseyev, F. A. Zonality in Oil and Gas Formation in the Earth's Crust Based on Isotope Studies: *Geologiya Nefti i Gaza*, pp. 62-67. English in *Petroleum Geology*, 1974, v. 12, pp. 191-192.
23. Grace, J. D. and G. F. Hart. Giant Gas Fields of Northern West Siberia. AAPG Bull. 1986, v. 70, no. 7, pp. 830-852.
24. Wirojangu, P., C. W. Kreidler, and D. A. Smith. Numerical Modeling of Regional Groundwater Flow in the Deep-Basin Brine Aquifer of the Palo Duro Basin, Texas Panhandle. Report of Investigation No. 159, Bureau of Economic Geology. University of Texas at Austin, 1986, pp. 1-68.
25. Powley, D. Subsurface Fluid Compartments. Lecture at the Tulsa Geological Society Meeting, Sept. 1990, Tulsa, Ok.
26. Szpakiewicz, M. Application of Natural Isotopes in Groundwater for Solving Environmental Problems. Department of Energy Report No. NIPER-450, 1990, pp. 1-70.

TABLE 1. - Isotopic composition of oil field brines from the North American basins
(modified from Montgomery and Perry, 1982)

Basin samples	$\delta^{18}\text{O}/^{16}\text{O}$ per mille	$\delta\text{D}/\text{H}$ per mille	Number of samples
Illinois	-10 to +4.5	-85 to +8	35
Michigan	-13.5 to +4.5	-110 to -25	24
Gulf Coast	+2.5 to +9.0	-13 to +18	10
Alberta	-12.5 to +3.0	-120 to -50	8

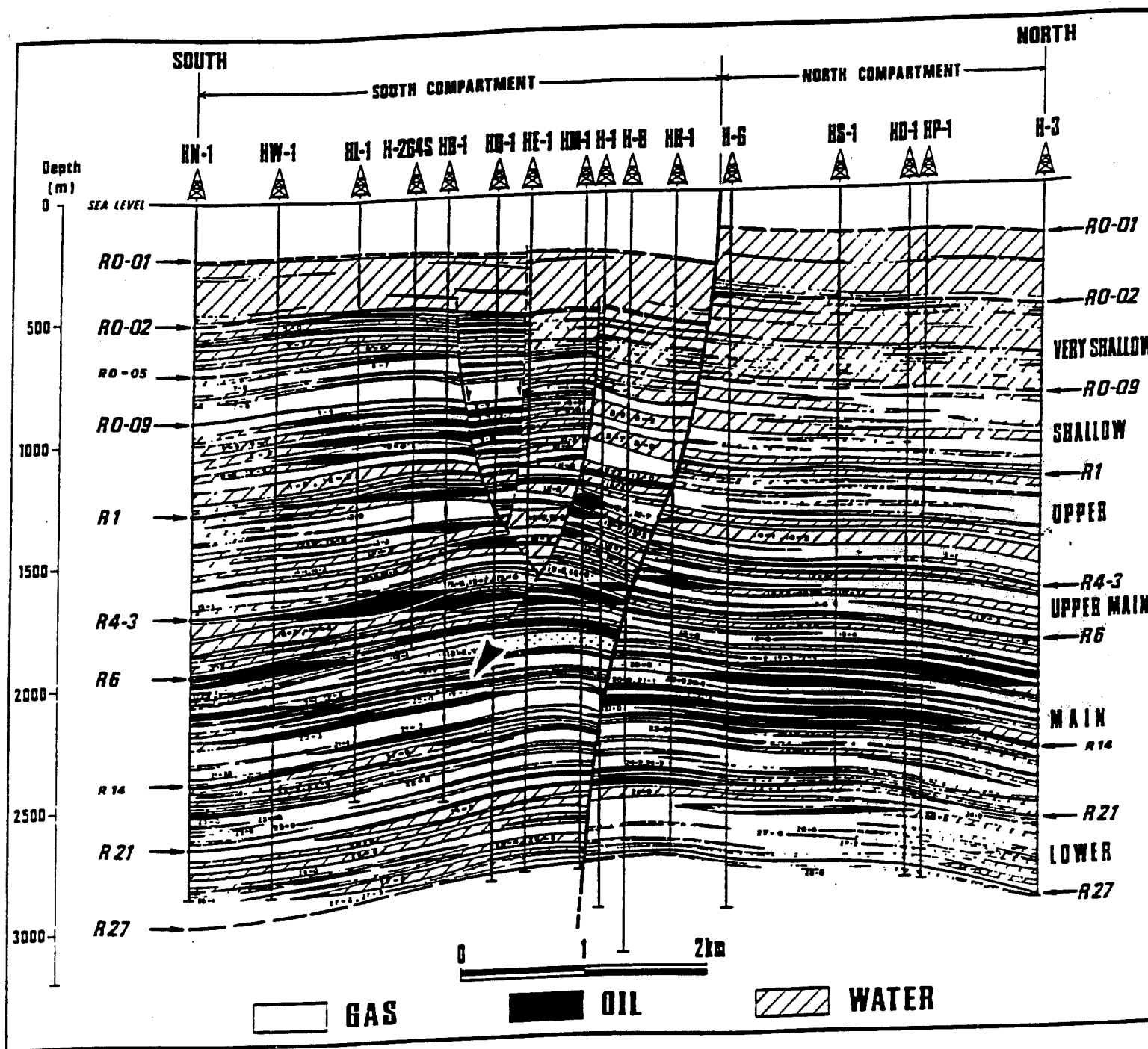


FIGURE 1. - Schematic north to south cross section of Handil field Indonesia indicating the multiple reservoirs and the distribution of the hydrocarbons. Note position of the 19-7 reservoir reached at depth of 1,970 m and located between R9 and R10 marker (arrow). The arrangement of sandstone bodies in the 19-7 reservoir is shown in fig. 2. After Verdier et al. 1980.

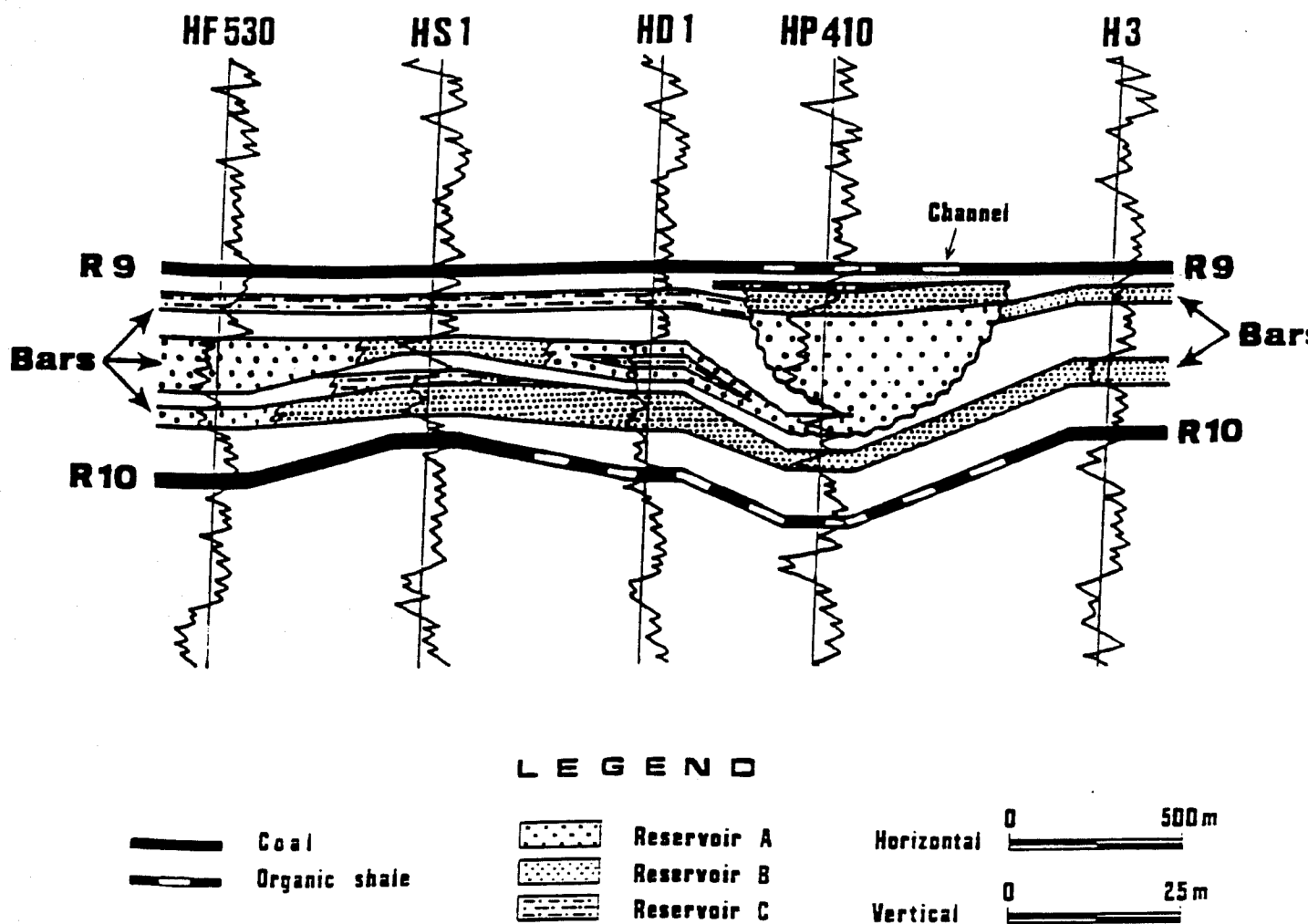


FIGURE 2. Complex organization of sandstone bodies within 19-7 reservoir, Handil field, Indonesia. Erosional feature (the upper channel) links the oil-bearing strata into one hydrodynamic system. There are no fluid incompatibilities or discrepancies in the pressure measurements between A, B, and C subreservoirs. Position of the 19-7 reservoir in the Handil multiple reservoir system is shown in fig. 1. After Verdier et al. 1980.

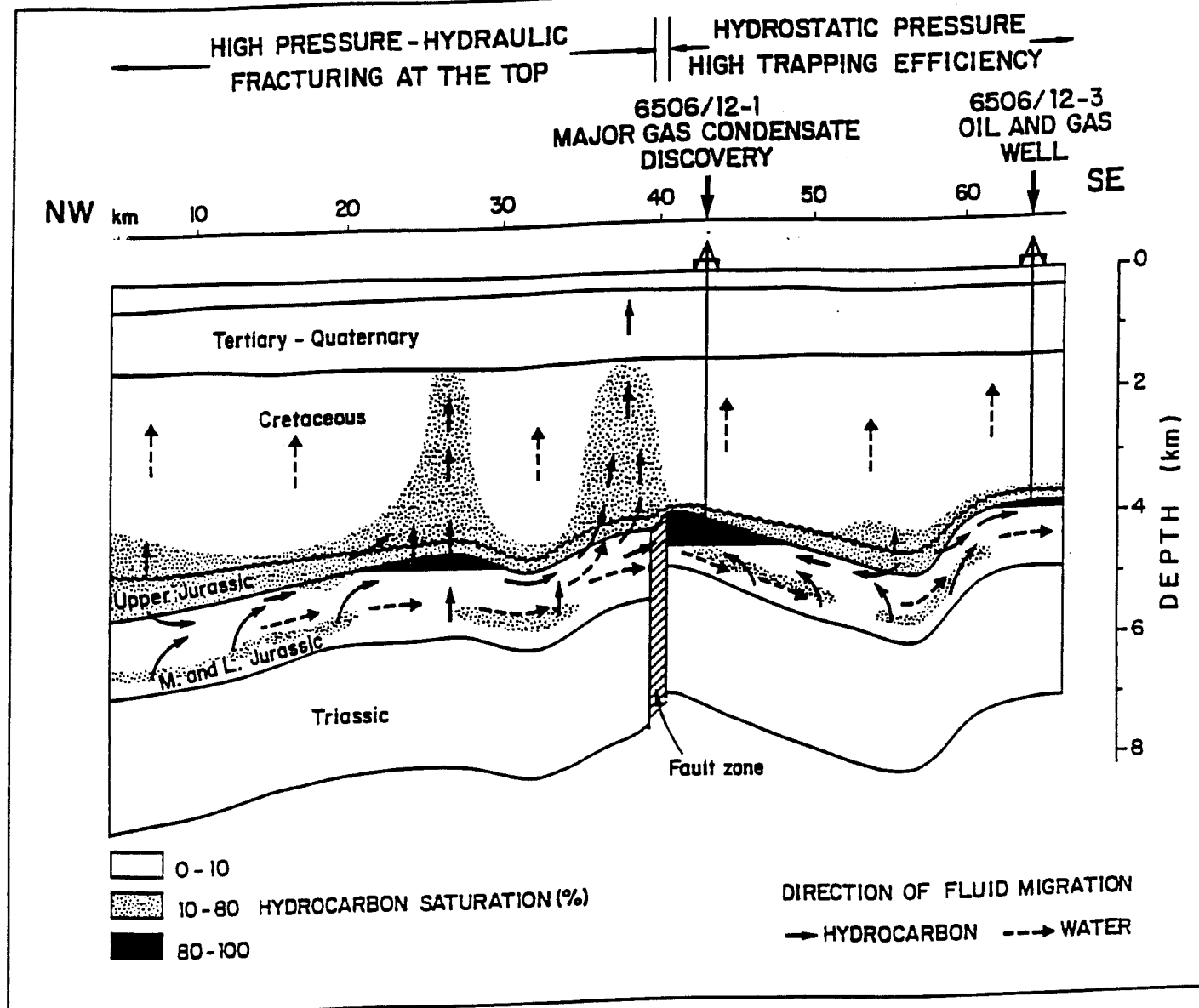


FIGURE 3. Migration model on cross section through Smorbukk hydrocarbon field, Maltenbanken, Viking graben, North Sea. Southeast part of the section is oil and gas productive because greater pressure in Cretaceous shales than in reservoir makes these shales a very efficient cap rock. Isotopic composition of fluids is predicted to be distinctly different in vertical profile. Northwest, reservoirs are highly overpressured and leak to the overlying strata through ruptured cap rock. There is no economic hydrocarbon accumulations north and west of sealed fault zone. Isotopic composition of fluids is predicted to be near uniform in vertical profile. Modified from Ungerer et al. 1990.